

First two sided limit on $\text{BR}(B_s \rightarrow \mu^+\mu^-)$

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SUSY 2011

$B_{s(d)} \rightarrow \mu^+ \mu^-$ Beyond the SM

- Indirect searches for new physics
- Look at processes that are suppressed in the SM
- Excellent place to spot non SM contributions

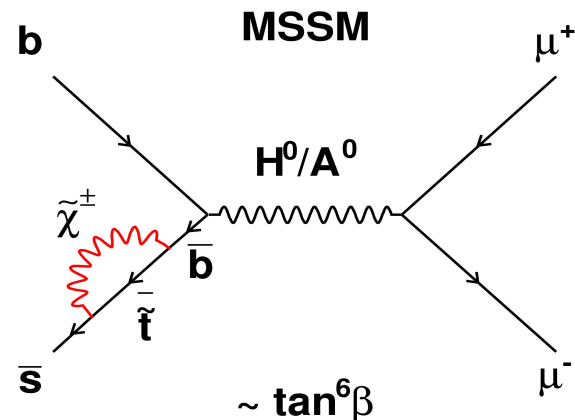
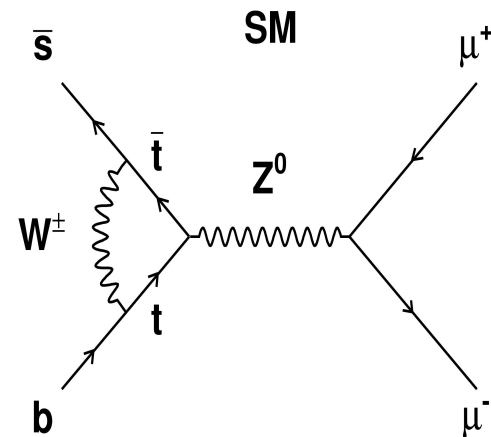
■ $B_{s(d)} \rightarrow \mu^+ \mu^-$

● SM:

- ◆ No tree level decay
- ◆ GIM, CKM and helicity suppressed
- ◆ $\text{BF}(B_s \rightarrow \mu^+ \mu^-) = 3.2 \pm 0.2 \times 10^{-9}$

● New Physics:

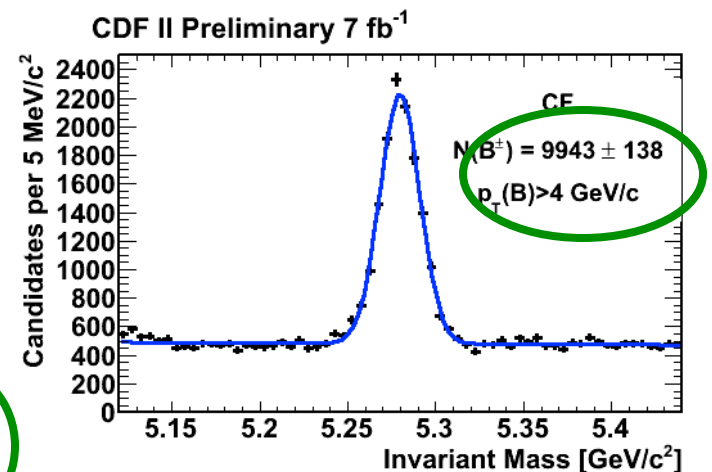
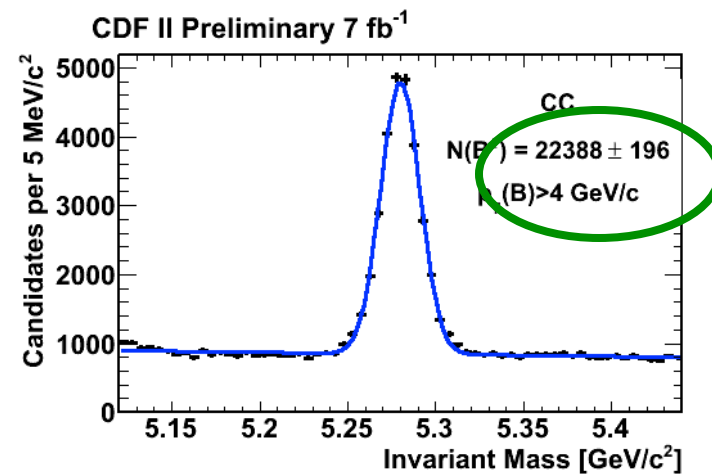
- ◆ Loop: MSSM: mSugra, Higgs Doublet
- ◆ Rate $\propto \tan^6 \beta / (M_A)^4$
- ◆ Large enhancement possible



$B_{s(d)} \rightarrow \mu^+ \mu^-$ Method

- Measure decay rate of $B_{s(d)} \rightarrow \mu^+ \mu^-$ relative to $B^+ \rightarrow J/\psi K^+$, $J/\psi \rightarrow \mu^+ \mu^-$
- Apply minimal selection, ensures sample of well measured dimuon events
- Final discrimination with NN
- Improvements vs. previous publication:
 - 20% additional signal acceptance. New triggered regions understood with additional data.
 - Expanded NN. 2x background rejection for same efficiency

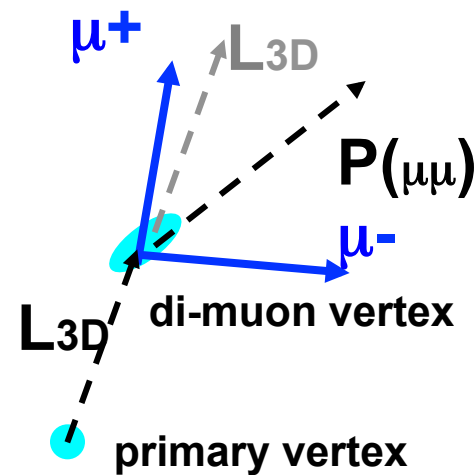
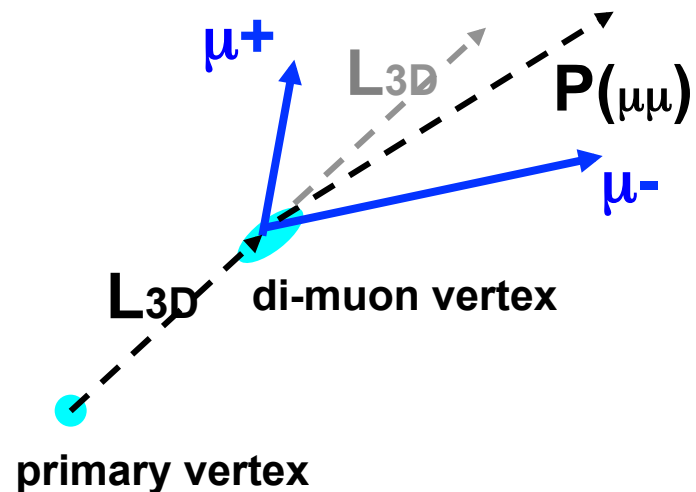
$$BF(B_s \rightarrow \mu^+ \mu^-) = \frac{(N_{cand} - N_{bg})}{\alpha_{B_s} \epsilon_{B_s}} \cdot \frac{\alpha_{B^+} \epsilon_{B^+}}{N_{B^+}} \cdot \frac{f_u}{f_s} \cdot \underbrace{BR(B^+ \rightarrow J/\psi K^+) \cdot BR(J/\psi \rightarrow \mu^+ \mu^-)}$$



5 X 10⁸ B_s events

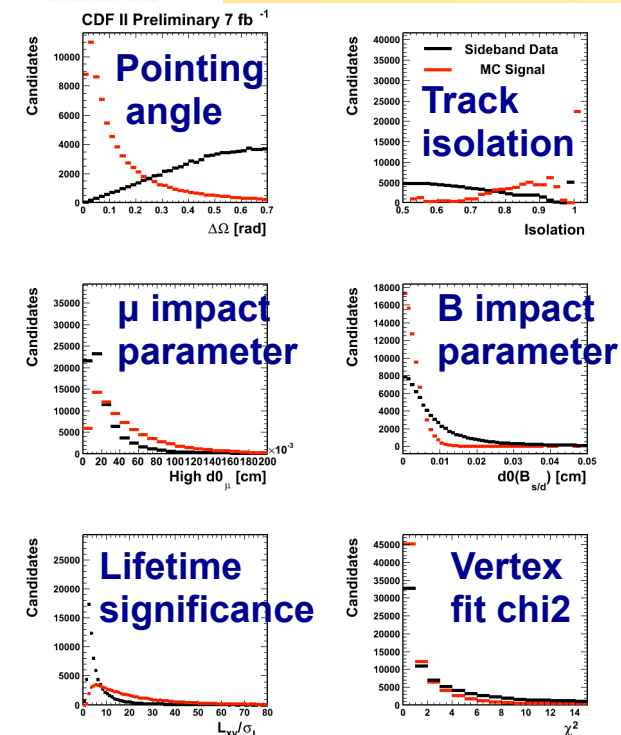
Signal vs. Background

- Need to discriminate signal from background
 - Reduce background by a factor of ~ 10000
- Signal characteristics
 - Final state fully reconstructed
 - B_s is long lived ($c\tau \sim 450 \mu\text{m}$)
 - B fragmentation is hard: few additional tracks
- Background contributions and characteristics
 - Sequential semi-leptonic decay: $b \rightarrow c\mu^-X \rightarrow \mu^+\mu^-X$
 - Double semileptonic decay: $b\bar{b} \rightarrow \mu^+\mu^-X$
 - Continuum $\mu^+\mu^-$
 - μ + fake, fake+fake
 - Partially reconstructed, lower p_T , short lived, doesn't point to the primary vertex, and has additional tracks

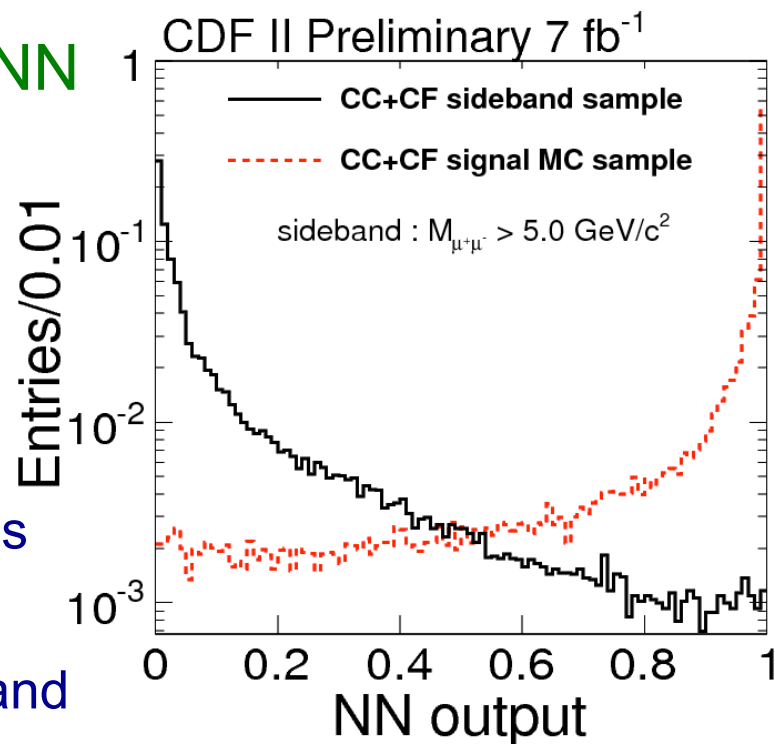


Cut on mass, lifetime, p_T , how well \vec{p} points to the vertex and isolation

Discriminating Variables



- 14 discriminating variables +
- Mass $m_{\mu\mu}$ 2.5 σ window: $\sigma = 24\text{MeV}/c^2$
 - First 5 variables at left are the most powerful
- Combine in NN

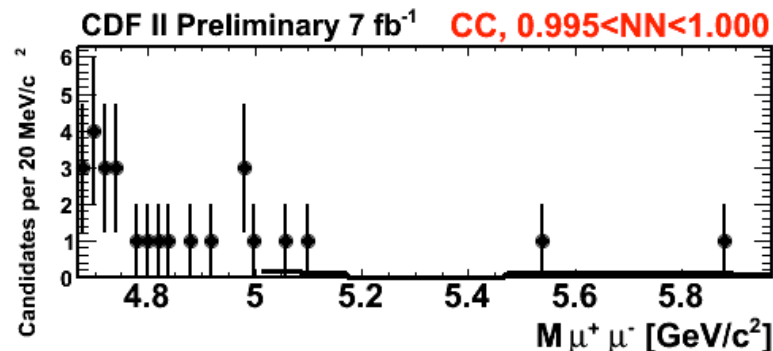
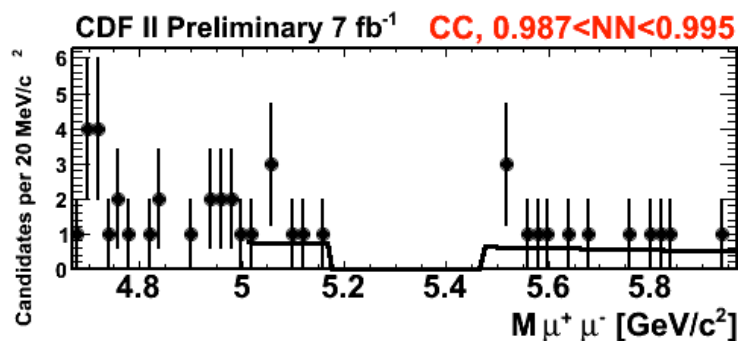
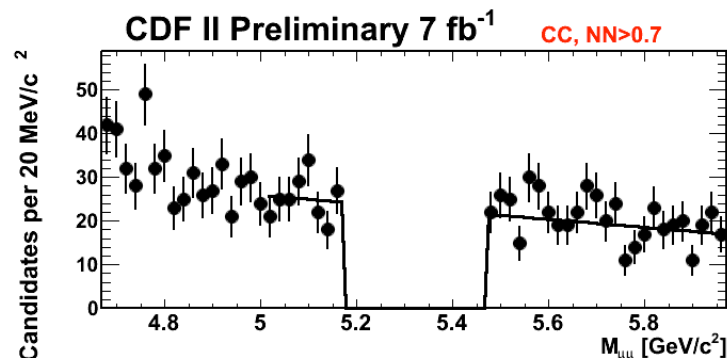


- Unbiased optimization based on simulated signal and data sidebands. Validate with B⁺
- Determine background by extrapolating mass sidebands: Extensively tested for mass bias
- Perform search in two detector regions(CC and CF), 8 NN bins(0.7-1.0) and 5 mass bins

Combinatoric background

Combinatoric background estimated by extrapolating mass sidebands

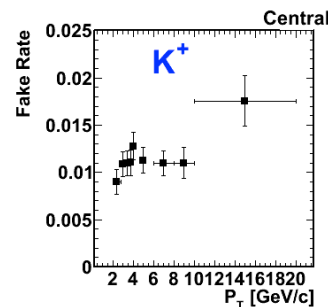
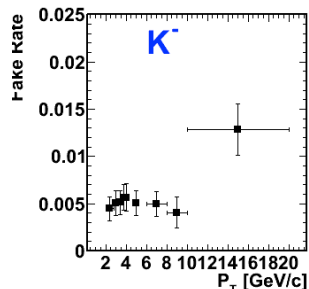
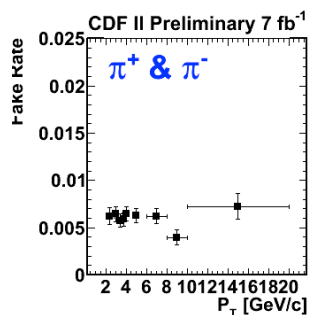
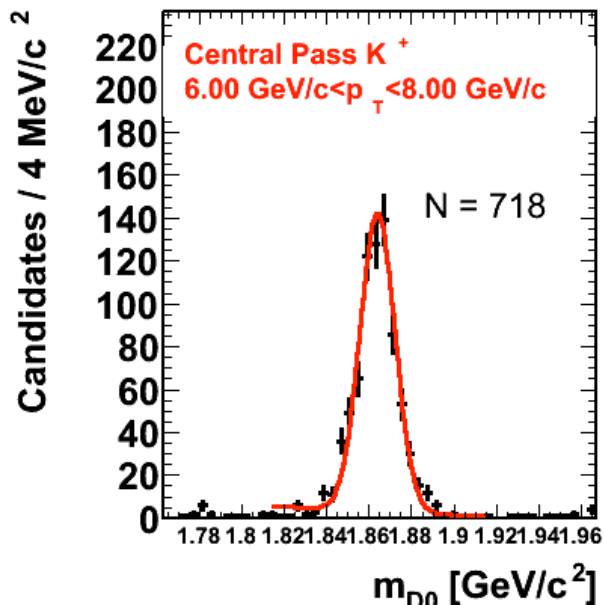
- Shape (slope) with mass determined using all events $NN > 0.7$
- Excludes masses below 5 GeV, $B \rightarrow \mu^+ \mu^- X$
- Systematic uncertainties from statistical power of sidebands samples and variation of the fit functions



B \rightarrow hh background

■ Peaking background dominated by B \rightarrow hh, h = pi K

- Rates of hadron misidentification as muons estimated from $D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$ decays
- Large sample allows determination of misidentification rate vs. pT and luminosity and study of run conditions dependence



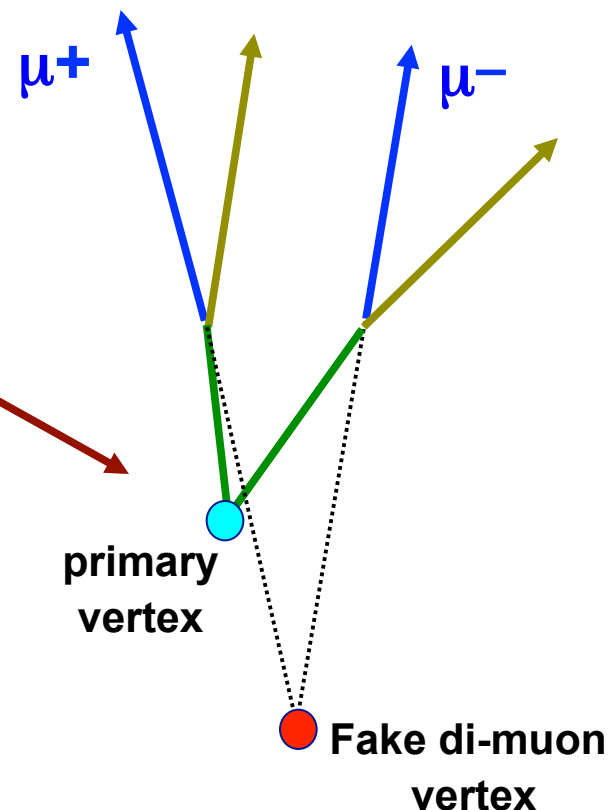
B_s backgrounds vs NN:
order 1% X1%
all but $B_s \rightarrow \pi\pi$ shifted
down in mass

NN Bin	CC	CF
$0.700 < NN < 0.970$	0.03 ± 0.01	$0.01 \pm < 0.01$
$0.970 < NN < 0.987$	$0.01 \pm < 0.01$	$0.01 \pm < 0.01$
$0.987 < NN < 0.995$	$0.02 \pm < 0.01$	$0.01 \pm < 0.01$
$0.995 < NN < 1.000$	0.08 ± 0.02	0.03 ± 0.01

For B_s search B \rightarrow hh background
1/10 the combinatoric

Control Regions

- Use independent data samples enriched in expected backgrounds to test estimates
 - OS-: opposite sign muons, **negative lifetime** (signal sample is OS+)
 - SS+ and SS-: same sign muons, positive and negative lifetime. No trigger matching
 - ** OS-, SS: Opposite side B hadrons
 - FM: fake μ enhanced, one μ fails the muon Id cuts. Has a significant $B \rightarrow hh$ contribution
 - ** FM: False muon backgrounds
- Compare predicted vs. observed # of bg. events:
For multiple NN cuts



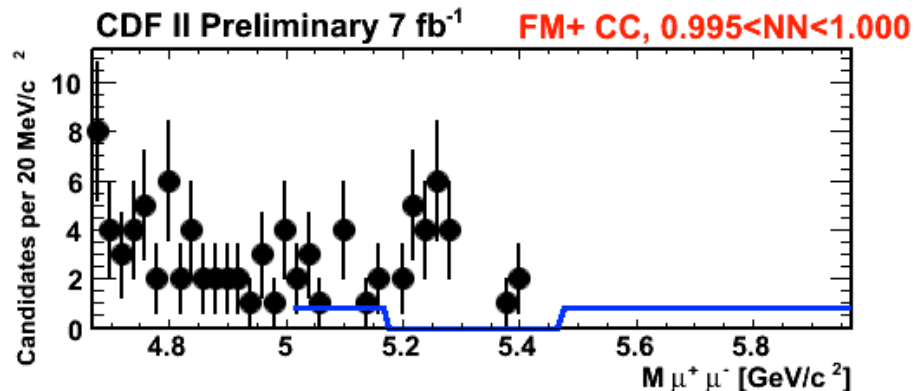
Control Regions

- Background predictions and observed background in control regions

sample	NN cut	CC		
		pred	obsv	prob(%)
OS-	$0.700 < NN < 0.760$	$217.4 \pm (12.5)$	203	77.7
	$0.760 < NN < 0.850$	$262.0 \pm (14.1)$	213	99.1
	$0.850 < NN < 0.900$	$117.9 \pm (8.6)$	120	44.7
	$0.900 < NN < 0.940$	$112.1 \pm (8.4)$	116	39.4
	$0.940 < NN < 0.970$	$112.7 \pm (8.4)$	108	64.2
	$0.970 < NN < 0.987$	$80.2 \pm (6.9)$	75	68.3
	$0.987 < NN < 0.995$	$67.6 \pm (6.3)$	41	99.8
SS+	$0.995 < NN < 1.000$	$32.5 \pm (4.2)$	35	37.5
	$0.700 < NN < 0.760$	$3.0 \pm (0.9)$	3	55.0
	$0.760 < NN < 0.850$	$3.3 \pm (1.0)$	5	25.4
	$0.850 < NN < 0.900$	$1.5 \pm (0.7)$	2	43.2
	$0.900 < NN < 0.940$	$0.9 \pm (0.5)$	1	56.8
	$0.940 < NN < 0.970$	$1.2 \pm (0.6)$	1	65.9
	$0.970 < NN < 0.987$	$1.5 \pm (0.7)$	2	43.2
SS-	$0.987 < NN < 0.995$	$0.3 \pm (0.3)$	0	74.1
	$0.995 < NN < 1.000$	$0.3 \pm (0.3)$	0	74.1
	$0.700 < NN < 0.760$	$5.7 \pm (1.3)$	8	23.7
	$0.760 < NN < 0.850$	$8.4 \pm (1.6)$	7	69.8
	$0.850 < NN < 0.900$	$3.3 \pm (1.0)$	6	14.3
	$0.900 < NN < 0.940$	$2.4 \pm (0.8)$	4	24.0
	$0.940 < NN < 0.970$	$2.4 \pm (0.8)$	4	24.0
FM+	$0.970 < NN < 0.987$	$2.1 \pm (0.8)$	0	12.2
	$0.987 < NN < 0.995$	$1.5 \pm (0.7)$	0	22.3
	$0.995 < NN < 1.000$	$0.3 \pm (0.3)$	1	30.0
	$0.700 < NN < 0.760$	$118.3 \pm (8.6)$	136	11.1
	$0.760 < NN < 0.850$	$110.5 \pm (8.3)$	121	22.3
	$0.850 < NN < 0.900$	$52.0 \pm (5.4)$	37	96.3
	$0.900 < NN < 0.940$	$37.3 \pm (4.5)$	37	53.0
	$0.940 < NN < 0.970$	$20.1 \pm (3.3)$	20	52.3
	$0.970 < NN < 0.987$	$8.3 \pm (2.0)$	6	77.1
	$0.987 < NN < 0.995$	$8.7 \pm (2.0)$	3	97.5
	$0.995 < NN < 1.000$	$20.8 \pm (3.5)$	24	30.7

$B \rightarrow hh$ contribution to FM control region

NN Bin	CC	CF
$0.700 < NN < 0.760$	$0.17 \pm (0.02)$	$0.02 \pm (0.01)$
$0.760 < NN < 0.850$	$0.18 \pm (0.02)$	$0.03 \pm (0.01)$
$0.850 < NN < 0.900$	$0.21 \pm (0.02)$	$0.03 \pm (0.01)$
$0.900 < NN < 0.940$	$0.22 \pm (0.02)$	$0.04 \pm (0.01)$
$0.940 < NN < 0.970$	$0.26 \pm (0.03)$	$0.04 \pm (0.01)$
$0.970 < NN < 0.987$	$0.42 \pm (0.05)$	$0.06 \pm (0.01)$
$0.987 < NN < 0.995$	$0.82 \pm (0.09)$	$0.11 \pm (0.02)$
$0.995 < NN < 1.000$	$8.65 \pm (0.93)$	$1.16 \pm (0.20)$



- 64 Independent checks of the background estimation method
- $B \rightarrow hh$ seen with expected mass shape and is well estimated

Expected Sensitivity

• Efficiencies and acceptances

	CC		CF	
$(\alpha_{B^+} / \alpha_{B_s})$	0.307 ± 0.018	$(\pm 6\%)$	0.197 ± 0.014	$(\pm 7\%)$
$(\epsilon_{B^+}^{trig} / \epsilon_{B_s}^{trig})$	0.99935 ± 0.00012	$(< 1\%)$	0.97974 ± 0.00016	$(< 1\%)$
$(\epsilon_{B^+}^{reco} / \epsilon_{B_s}^{reco})$	0.85 ± 0.06	$(\pm 8\%)$	0.84 ± 0.06	$(\pm 9\%)$
$\epsilon_{B_s}^{NN} (NN > 0.70)$	0.915 ± 0.042	$(\pm 4\%)$	0.864 ± 0.040	$(\pm 4\%)$
$\epsilon_{B_s}^{NN} (NN > 0.995)$	0.461 ± 0.021	$(\pm 5\%)$	0.468 ± 0.022	$(\pm 5\%)$
N_{B^+}	22388 ± 196	$(\pm 1\%)$	9943 ± 138	$(\pm 1\%)$
f_u / f_s	3.59 ± 0.37	$(\pm 13\%)$	3.59 ± 0.37	$(\pm 13\%)$
$BR(B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+)$	$(6.01 \pm 0.21) \times 10^{-5}$	$(\pm 4\%)$	$(6.01 \pm 0.21) \times 10^{-5}$	$(\pm 4\%)$
SES (All bins)	$(2.9 \pm 0.5) \times 10^{-9}$	$(\pm 18\%)$	$(4.0 \pm 0.7) \times 10^{-9}$	$(\pm 18\%)$

**Have reached single event
sensitivity to the SM rate of $B_s \rightarrow \mu^+ \mu^-$**

Expected Sensitivity

$B_s \rightarrow \mu^+ \mu^-$ CC

NN Bin	ϵ_{NN}	B \rightarrow hh Bkg	Total Bkg	Exp SM Signal
$0.700 < NN < 0.970$	20%	0.03	129.24 ± 6.50	0.26 ± 0.05
$0.970 < NN < 0.987$	8%	< 0.01	7.91 ± 1.27	0.11 ± 0.02
$0.987 < NN < 0.995$	12%	0.02	3.95 ± 0.89	0.16 ± 0.03
$0.995 < NN < 1.000$	46%	0.08	0.79 ± 0.40	0.59 ± 0.11

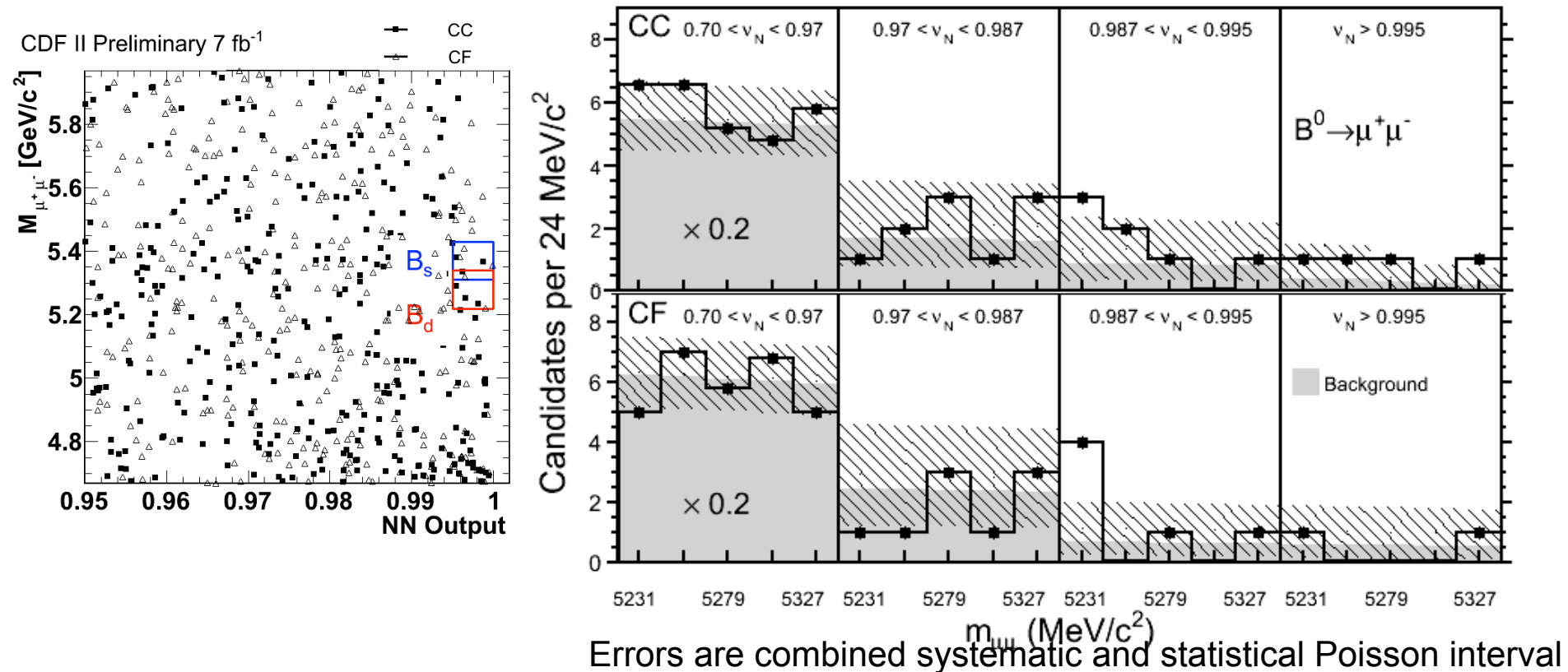
$B_s \rightarrow \mu^+ \mu^-$ CF

NN Bin	ϵ_{NN}	B \rightarrow hh Bkg	Total Bkg	Exp SM Signal
$0.700 < NN < 0.970$	21%	0.01	146.29 ± 7.00	0.19 ± 0.04
$0.970 < NN < 0.987$	10%	0.01	11.57 ± 1.57	0.09 ± 0.02
$0.987 < NN < 0.995$	8%	0.01	3.25 ± 0.82	0.08 ± 0.01
$0.995 < NN < 1.000$	46%	0.03	2.64 ± 0.74	0.43 ± 0.08

Expected B_s Limit: 1.5×10^{-8} at 95% CL

Expected B_d Limit: 4.6×10^{-9} at 95% CL

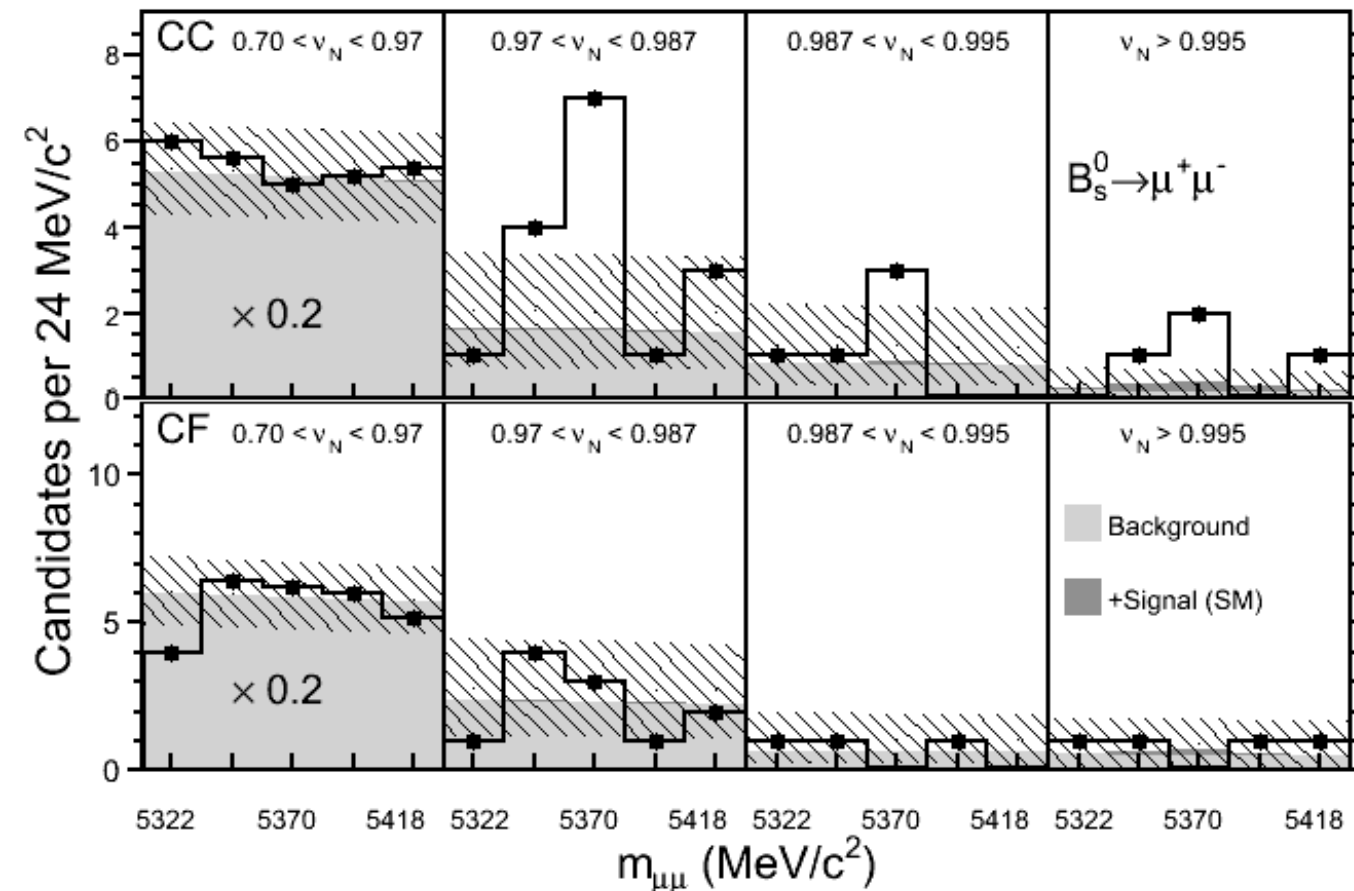
B^0 Results



- No significant excess seen in B^0 mass window
- Limits using the CLs technique, incorporating systematic uncertainties

$$BF(B_d \rightarrow \mu^+\mu^-) < 6.0 \times 10^{-9} \text{ at 95\% CL}$$

B_s Results



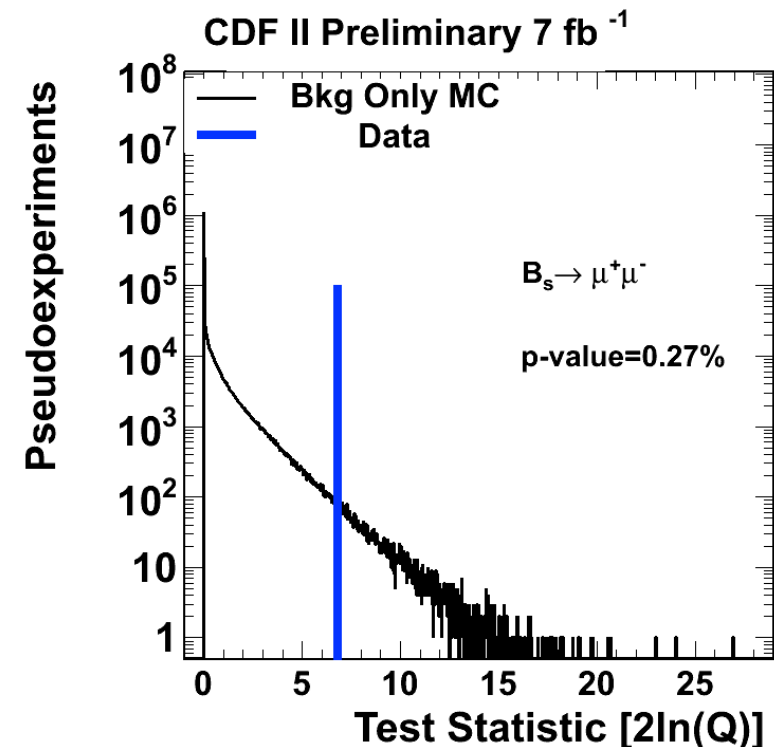
Excesses over
expected
backgrounds
observed in B_s CC
channel

- Limit set in the assumption that the observed events are from background processes

$$BF(B_s \rightarrow \mu^+ \mu^-) < 4.0 \times 10^{-8} \text{ at 95\% CL}$$

B_s P Values

- P values in the background only and background + SM signal hypothesis
- Found by comparing an ensemble of pseudo experiments for each hypothesis to the observed data
 - Systematic uncertainties are included in the pseudo experiments

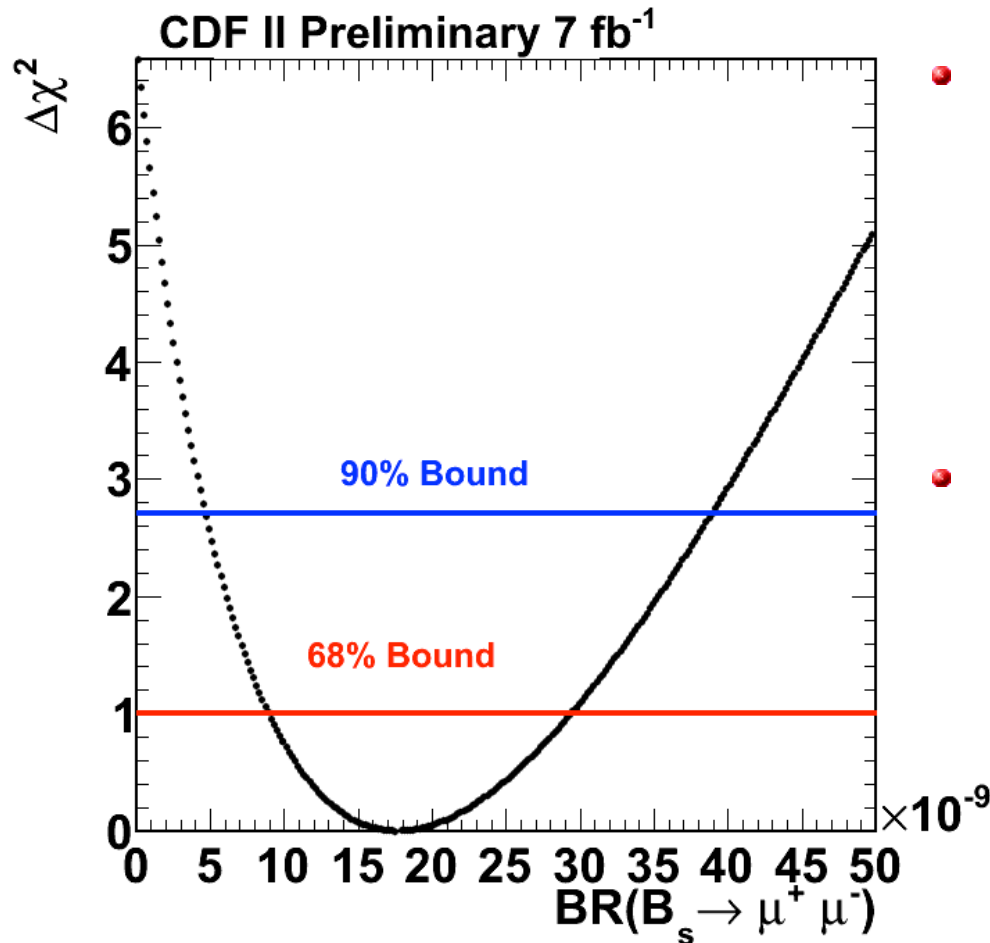


P Value B^0 : 23.3%

P Value B_s : 0.27%

P Value B_s (with SM signal): 1.92%

$BF(B_s \rightarrow \mu^+ \mu^-)$



- $BF(B_s \rightarrow \mu^+ \mu^-)$ in the hypothesis that the observed events have a significant contribution from either a SM or a new physics source of $B_s \rightarrow \mu^+ \mu^-$
- 90% C.L. interval $BF(B_s \rightarrow \mu^+ \mu^-)$ using a simple likelihood fit

$$4.6 \times 10^{-9} < BF(B_s \rightarrow \mu^+ \mu^-) < 3.9 \times 10^{-8} \text{ at 90\% C.L.}$$

$$BF(B_s \rightarrow \mu^+ \mu^-) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$$

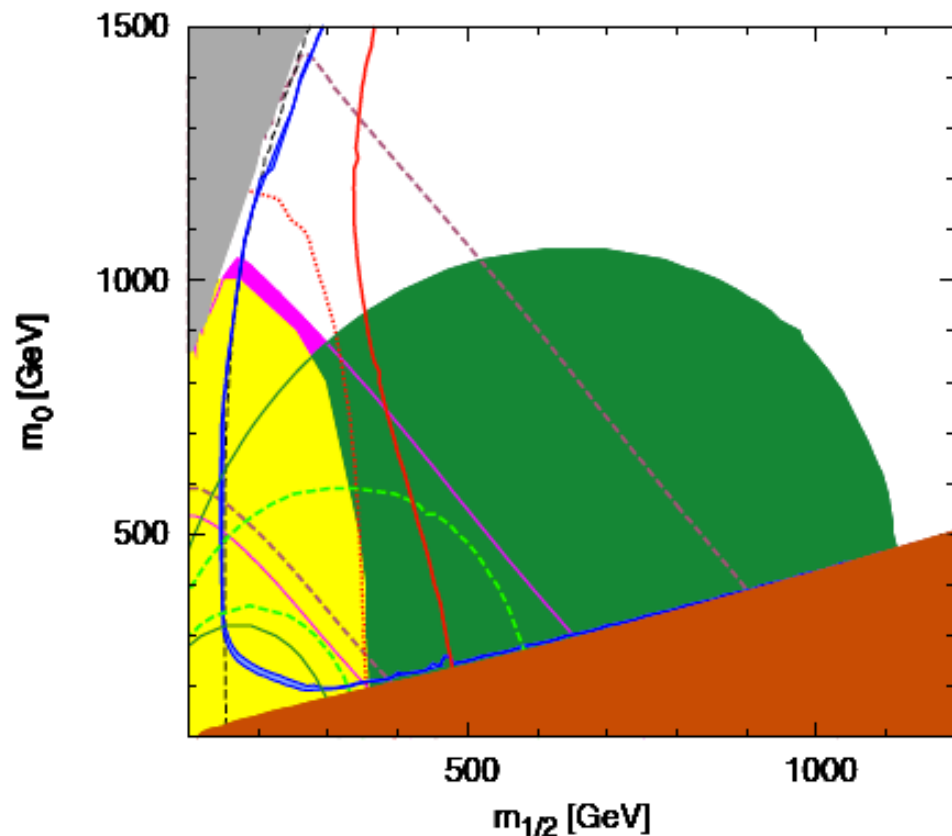
$B_s \rightarrow \mu^+ \mu^-$ Conclusion

- First significant excess observed in a $B_s \rightarrow \mu^+ \mu^-$ search

- Bounds set at 90C.L.

$$4.6 \times 10^{-9} < BF(B_s \rightarrow \mu^+ \mu^-) < 3.9 \times 10^{-8}$$

mSUGRA/CMSSM, $\tan \beta=40$, $A_0=0$, $\mu>0$



Example of physics reach

**Green area of m_0 vs. $m_{1/2}$
CMSSM plane favoured by
 $B_s \rightarrow \mu^+ \mu^-$ result**

**Would indicate reasonably
detectable super partner
masses and high $\tan(\beta)$**

**Could be exciting times
ahead!**

hep-ph 1107.3020, Dutta, Mimura, Santoso

Backup Material

Tevatron and CDF

- Tevatron: 2TeV $p\bar{p}$ collider

- CDF properties

- Silicon Tracker

EXCELLENT TRACKING

- $|\eta| < 2$, 90cm long, $r_{L00} = 1.3 - 1.6$ cm

- Drift Chamber(COT)

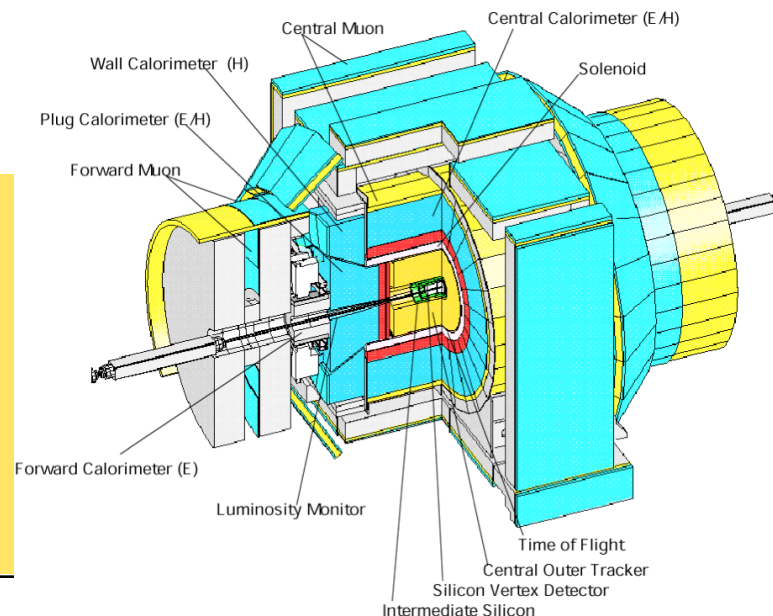
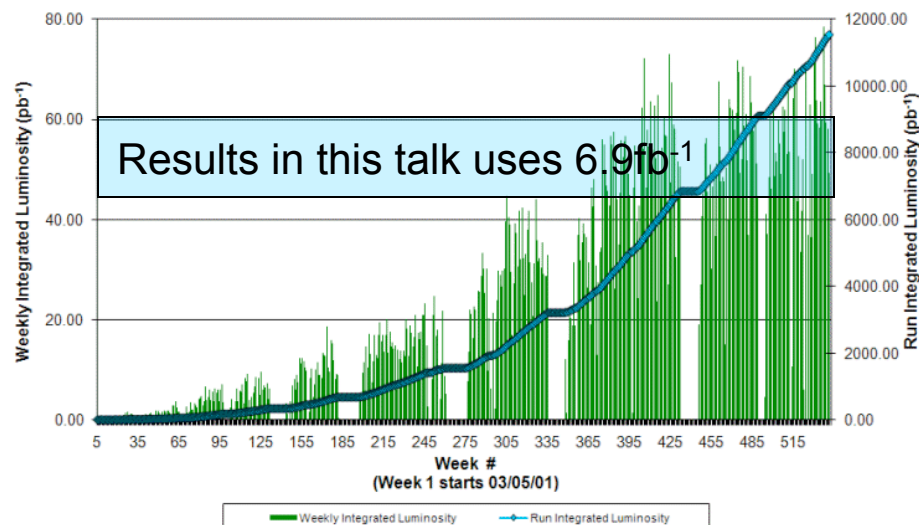
- 96 layers between 44 and 132cm

- Muon coverage

- Triggered to $|\eta| < 1.0$

TRIGGERED AT 1.5 GeV/c

Collider Run II Integrated Luminosity



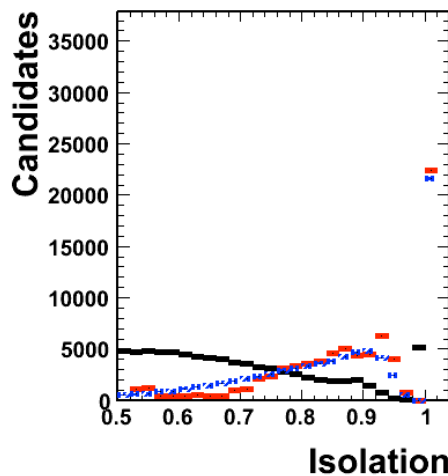
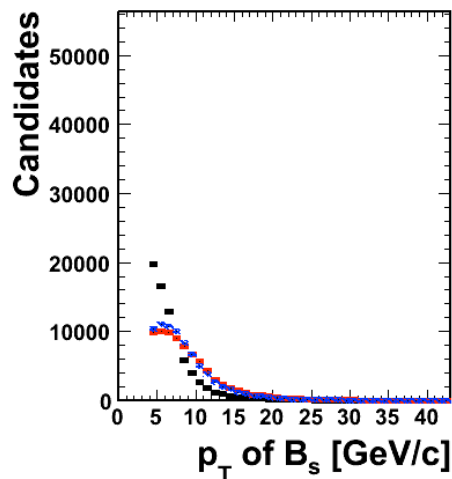
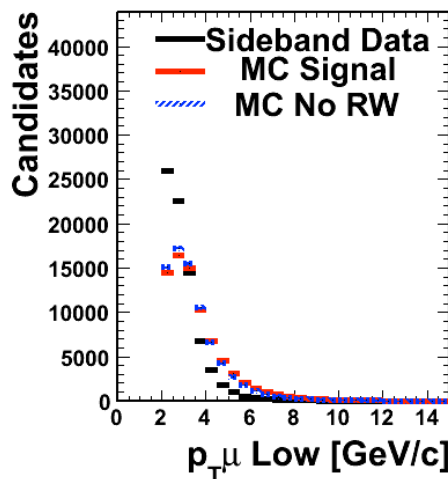
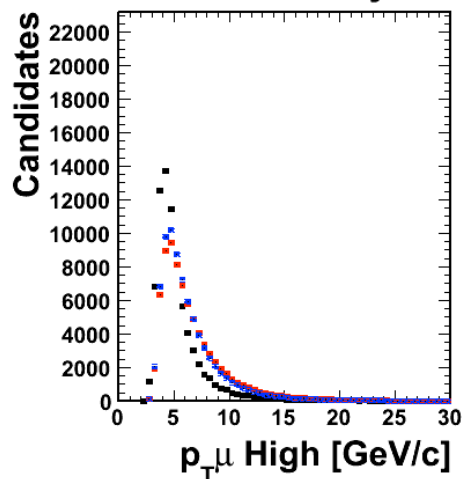
$B_{s(d)} \rightarrow \mu^+\mu^-$ benefits from the large integrated lumi of the Tevatron and the excellent mass and vertexing resolution of the CDF detector

$B_{s(d)} \rightarrow \mu^+ \mu^-$ Method

- Estimate all relative selection acceptances and efficiencies.
- Identify variables that discriminate signal and background
 - Design multivariate discriminant, NN, for background rejection
 - Unbiased optimization based on Pythia signal MC and part of mass sidebands.
 - Validate variable modelling and NN performance on B^+ data
- Estimate combinatoric background level from sidebands
- Separately estimate $B \rightarrow hh$
 - Validate background prediction method in control regions designed to be enhanced in expected backgrounds

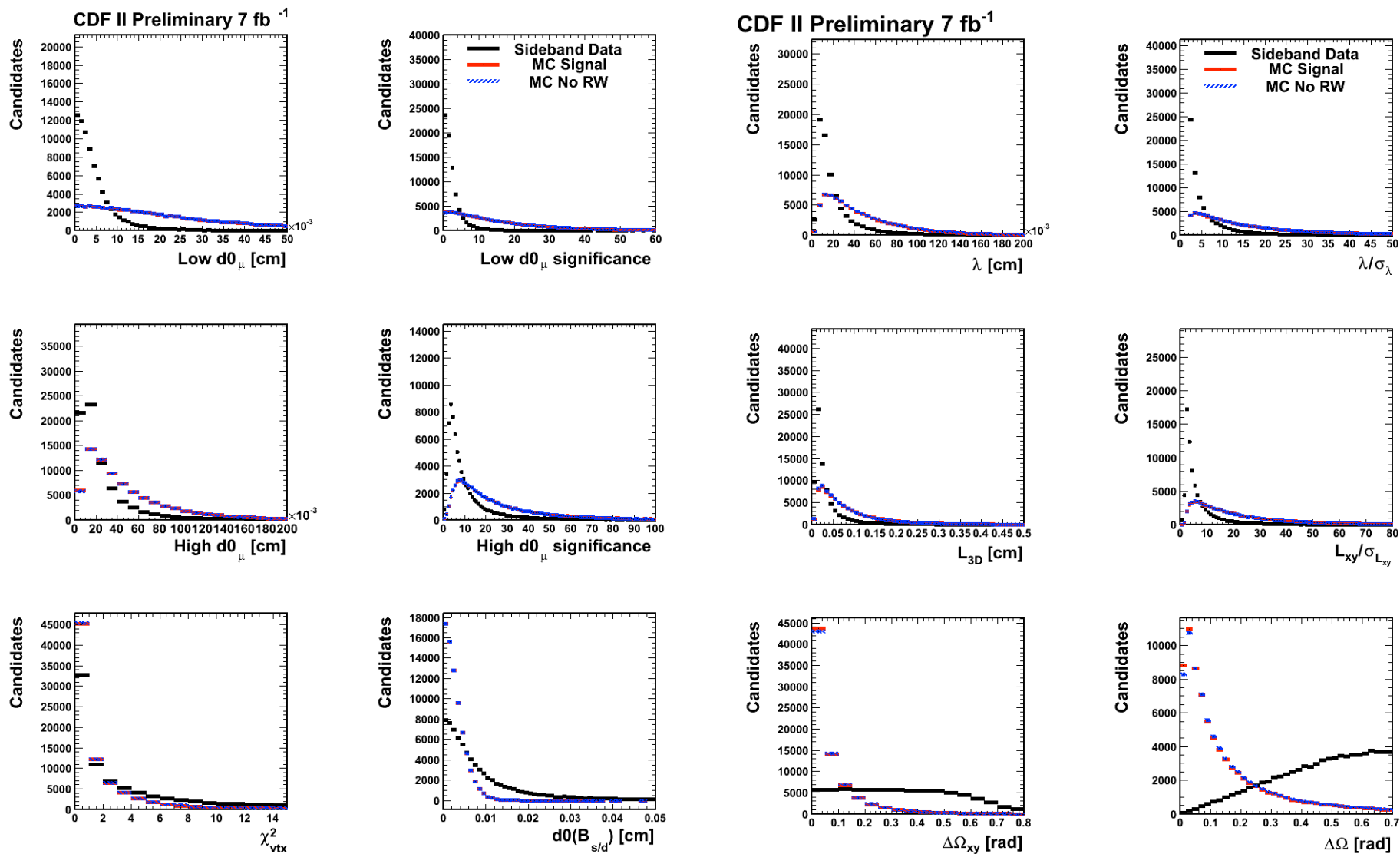
Discriminating Variables

CDF II Preliminary 7 fb⁻¹



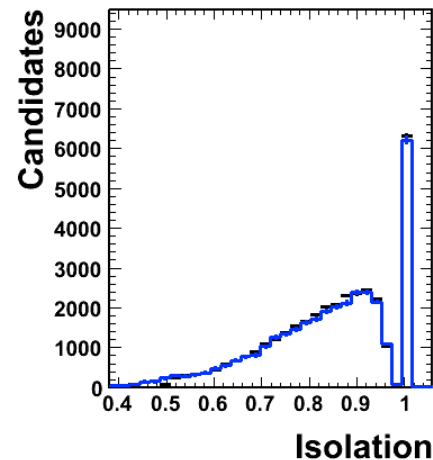
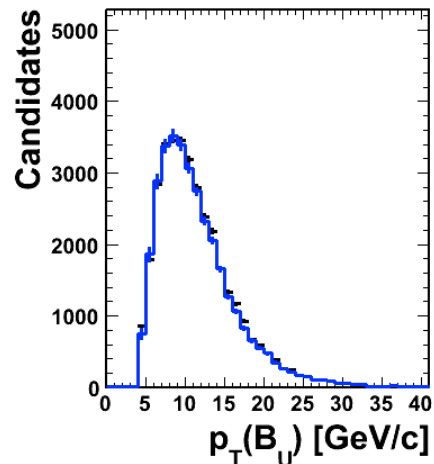
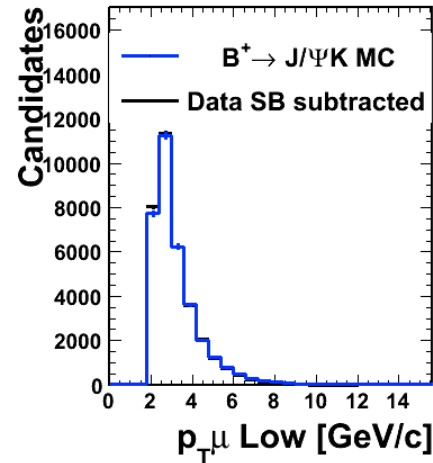
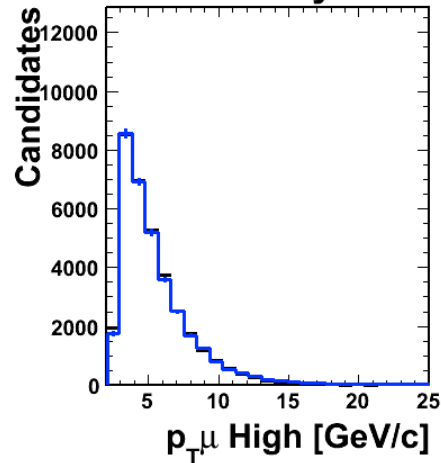
- BSignal simulated with Pythia
- Reweighed to match observed B_s p_T and isolation distributions

Discriminating Variables



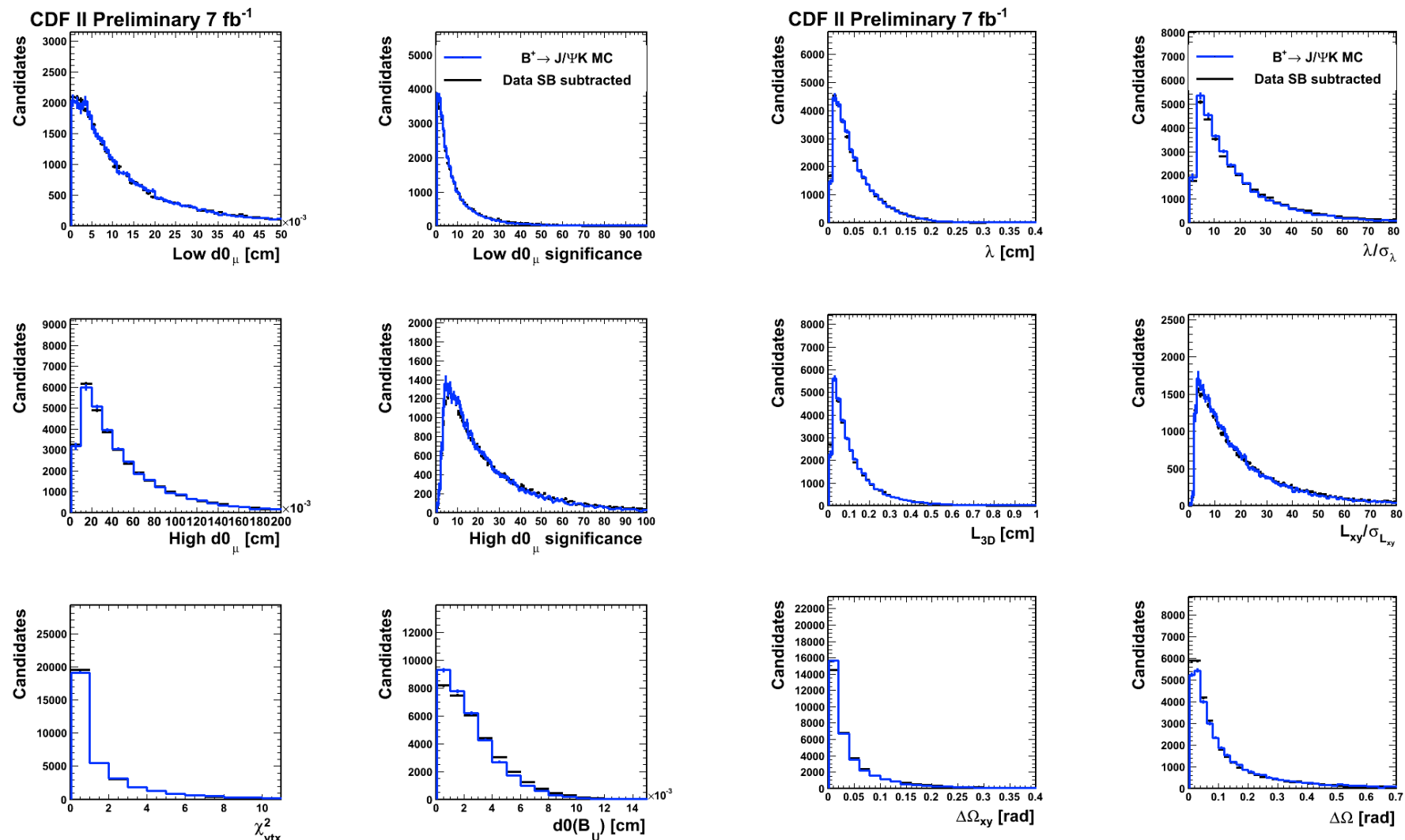
Variables: Validation

CDF II Preliminary 7 fb⁻¹

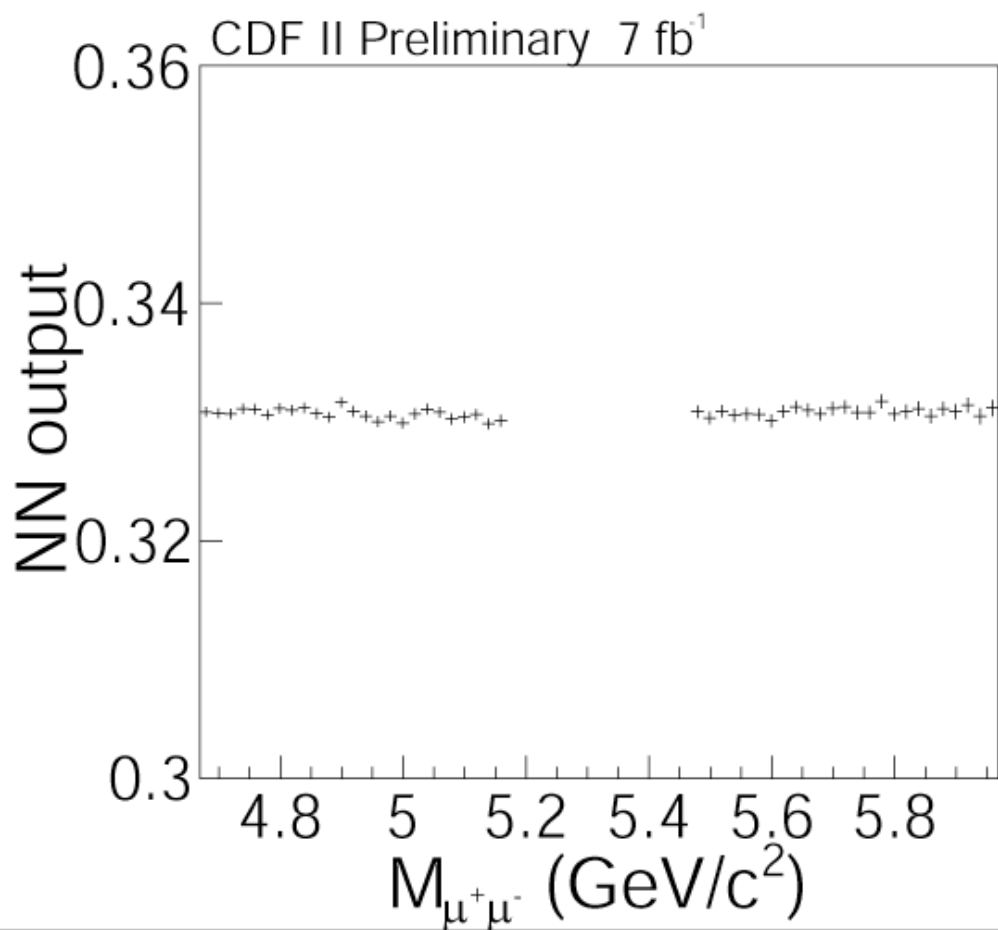


- $B^+ \rightarrow J/\psi K^+, J/\psi \rightarrow \mu^+ \mu^-$
sample used to
validate kinematic, NN
variables, and NN
performance
- Simulated using Pythia
as with signal same
 - Reweighed to match
observed B^+ p_T and
isolation distributions

Variables: Validation

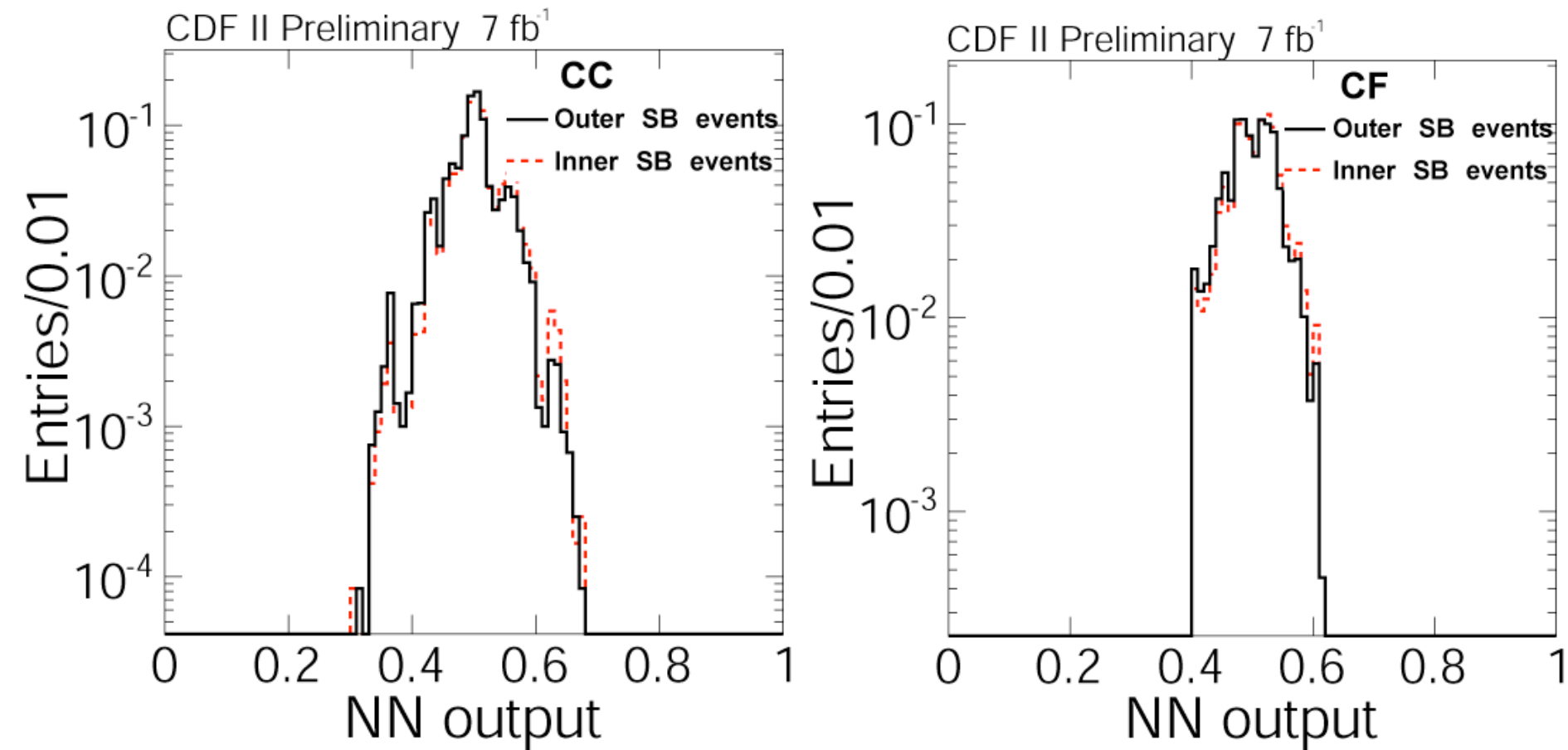


Mass Bias



- Search method requires there be no mass dependence in the NN
 - Combinatoric background estimated by extrapolating
 - Shape (slope) with mass determined using all events $NN > 0.7$
 - Check for NN correlation with mass in sideband and control sample
 - Test if NN training can distinguish mass

Mass Bias

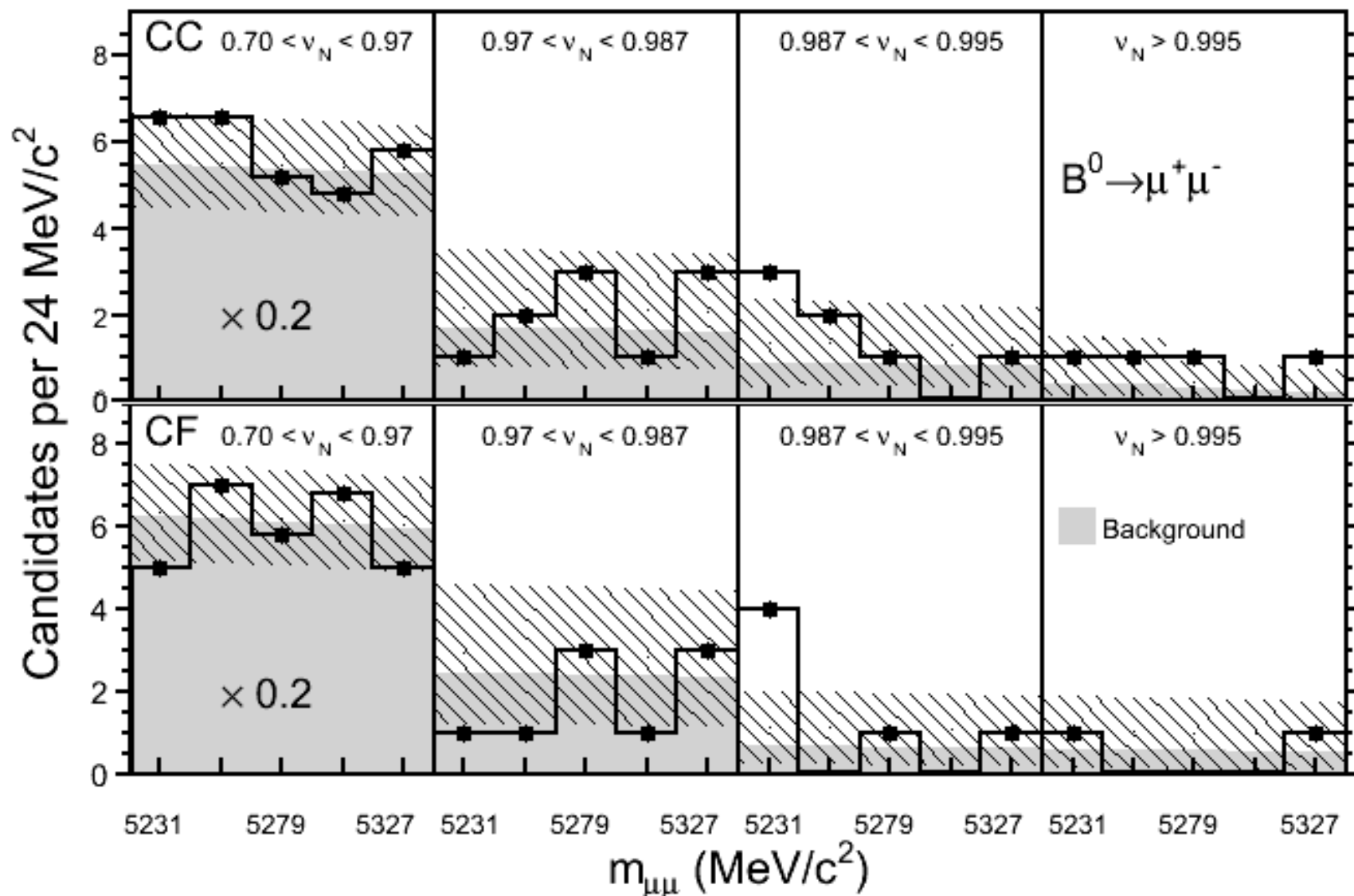


Result

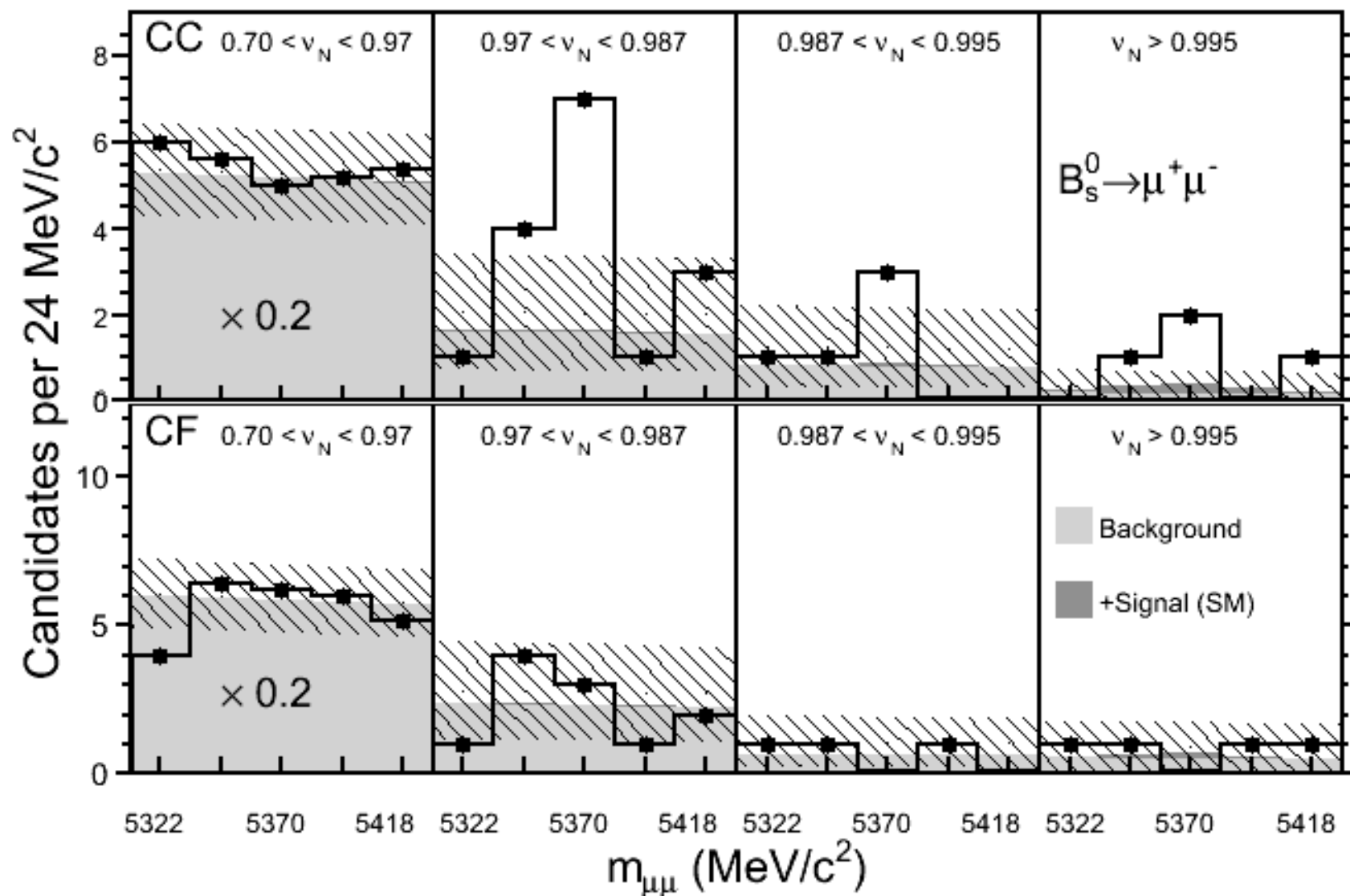
Mass Bin (GeV/c ²)		5.31-5.334	5.334-5.358	5.358-5.382	5.382-5.406	5.406-5.43	Total
CC NN bin	Exp Bkg	8.02±0.62	7.94±0.61	7.87±0.61	7.79±0.6	7.71±0.59	39.34
0.7-0.76	Obs	9	6	6	2	5	28
CC NN bin	Exp Bkg	8.43±0.64	8.34±0.63	8.26±0.62	8.18±0.62	8.1±0.61	41.32
0.76-0.85	Obs	8	6	11	11	7	43
CC NN bin	Exp Bkg	3.55±0.39	3.51±0.39	3.48±0.39	3.44±0.38	3.41±0.38	17.4
0.85-0.9	Obs	5	6	2	5	4	22
CC NN bin	Exp Bkg	3.51±0.39	3.47±0.39	3.44±0.38	3.41±0.38	3.37±0.38	17.2
0.9-0.94	Obs	4	5	4	5	7	25
CC NN bin	Exp Bkg	2.87±0.35	2.84±0.35	2.81±0.34	2.78±0.34	2.75±0.34	14.04
0.94-0.97	Obs	4	5	2	3	4	18
CC NN bin	Exp Bkg	1.62±0.49	1.60±0.48	1.58±0.47	1.57±0.47	1.55±0.46	7.92
0.97-0.987	Obs	1	4	7	1	3	16
CC NN bin	Exp Bkg	0.82±0.27	0.80±0.27	0.79±0.26	0.78±0.26	0.78±0.26	3.97
0.987-0.995	Obs	1	1	3	0	0	5
CC NN bin	Exp Bkg	0.21±0.14	0.18±0.13	0.16±0.12	0.16±0.12	0.16±0.12	0.87
0.995-1	Obs	0	1	2	0	1	4
CF NN bin	Exp Bkg	8.49±0.65	8.39±0.64	8.28±0.63	8.17±0.62	8.07±0.61	41.4
0.7-0.76	Obs	8	13	9	9	9	48
CF NN bin	Exp Bkg	9.45±0.69	9.33±0.68	9.21±0.67	9.1±0.66	8.98±0.65	46.07
0.76-0.85	Obs	7	8	7	11	4	37
CF NN bin	Exp Bkg	4.91±0.48	4.85±0.47	4.79±0.46	4.73±0.46	4.67±0.45	23.95
0.85-0.9	Obs	1	5	6	3	5	20
CF NN bin	Exp Bkg	3.87±0.42	3.82±0.41	3.77±0.41	3.73±0.4	3.68±0.4	18.88
0.9-0.94	Obs	4	1	6	3	3	17
CF NN bin	Exp Bkg	3.29±0.38	3.25±0.38	3.21±0.37	3.17±0.37	3.12±0.36	16.04
0.94-0.97	Obs	0	5	3	4	5	17
CF NN bin	Exp Bkg	2.38±0.56	2.34±0.55	2.31±0.54	2.28±0.54	2.25±0.53	11.57
0.97-0.987	Obs	1	4	3	1	2	11
CF NN bin	Exp Bkg	0.67±0.24	0.66±0.24	0.65±0.24	0.64±0.23	0.63±0.22	3.25
0.987-0.995	Obs	1	1	0	1	0	3
CF NN bin	Exp Bkg	0.56±0.39	0.54±0.38	0.53±0.38	0.52±0.37	0.51±0.36	2.66
0.995-1	Obs	1	1	0	1	1	4

Table: B_S signal window for CC(top) and CF(bottom): Expected backgrounds, including $B \rightarrow hh$, and number of observed events.

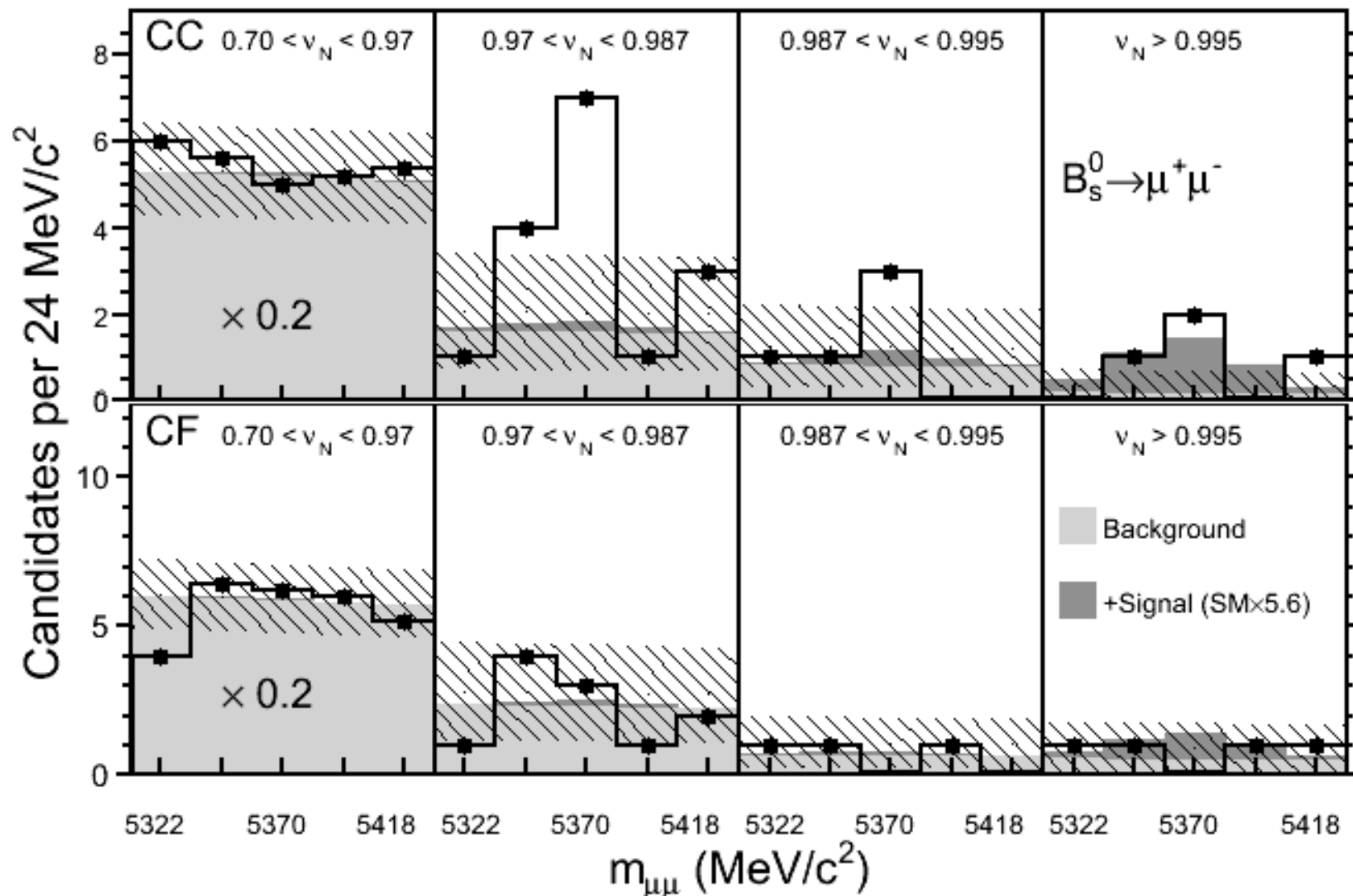
Result B^0



Results B_s



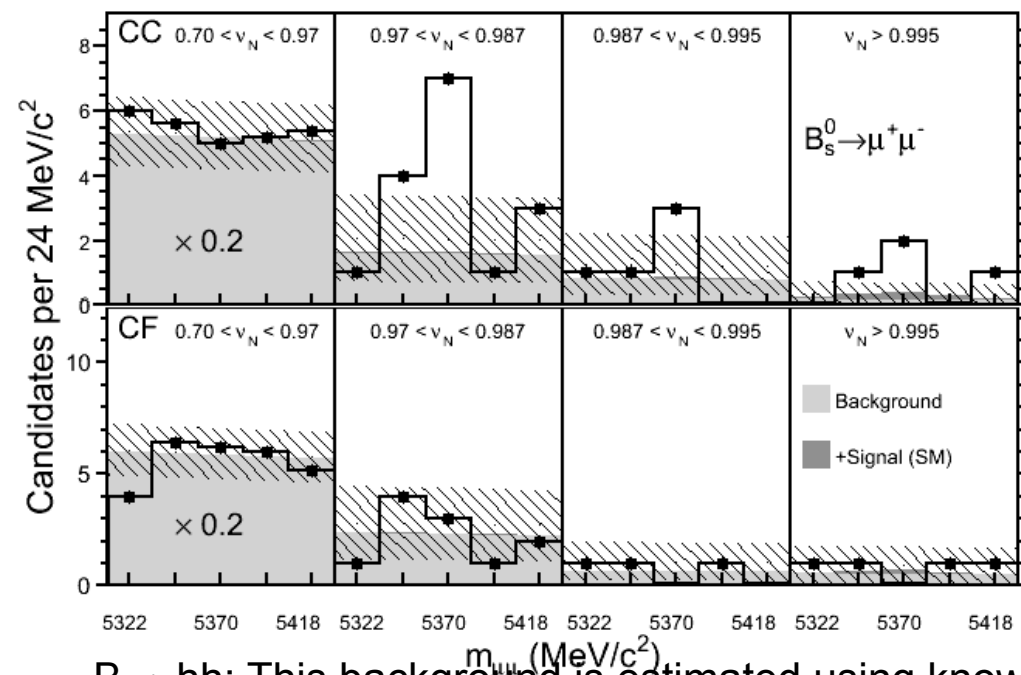
Results B_s



Test Statistic and Interpretation

- $-2\ln(Q)$, $Q=L(s+b|\text{data})/L(b|\text{data})$
- L is a likelihood obtained by multiplying all 80 Poisson probabilities of hypothesis $s+b$ or b given the observed data. The likelihood is minimized with respect to nuisance parameters that model the systematic uncertainties and a freely floating parameter for the signal.
- P values compare the values of $-2\ln(Q)$ observed in data to a ensemble of pseudo experiments in a given hypothesis.
- The most likely value of the signal is fit using the same likelihood and the confidence intervals are determined by using the change in χ^2

B_s Results. Third CC bin



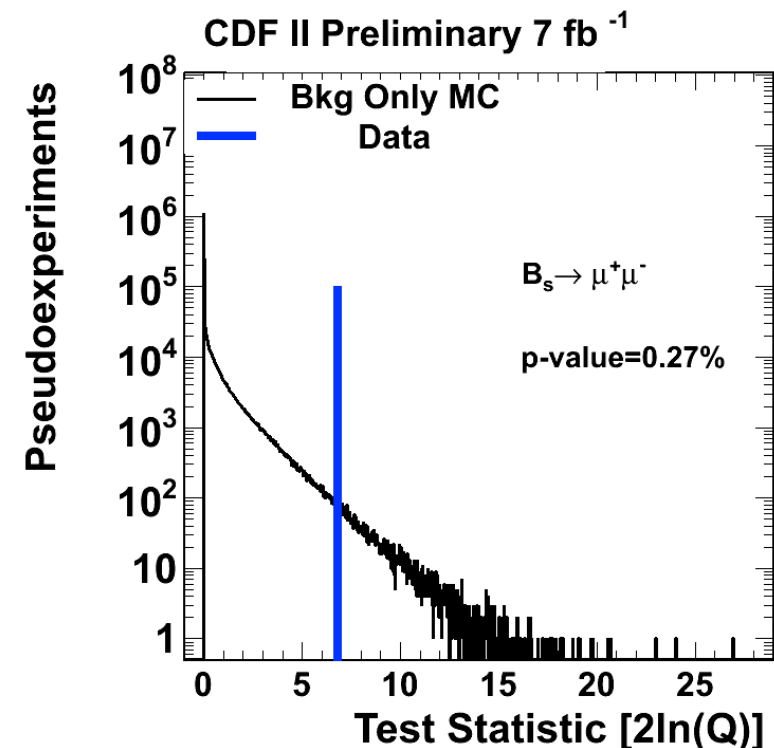
Significant excess also observed in the third bin of the B_s CC channel. Given current limits there bin has no expectation of signal at the level observed in this bin.

Analysis of possible sources:

- $B \rightarrow hh$: This background is estimated using known BFs and high statistics samples to determine fake rates. It is observed in the FM fake region at the expected rate. Also the mass resolution of CDF is well understood and this background should occur primarily at lower masses.
- Mass bias: No similar background is seen in the B^0 and the control region show no evidence of a similar mass bias.
- Highest probable source is a fluctuation of known backgrounds: order 1% chance. Not unlikely with 80 bins.

P Values

- P values in the background only and background + SM signal hypothesis
- Found by comparing an ensemble of pseudo experiments for each hypothesis to the observed data
 - Systematic uncertainties are included in the pseudo experiments



P Value B^0 : 23.3%

P Value B_s : 0.27%

P Value B_s : 0.66%
Only bins with significant signal expectation

P Value B_s (with SM signal): 1.92%

P Value B_s (with SM signal): 4.14%
Only bins with significant signal expectation

Comparison of Experiments

- LHCb: $BF(B_s \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-8}$ at 95% CL
 - CMS: $BF(B_s \rightarrow \mu^+\mu^-) < 4.0 \times 10^{-8}$ at 95% CL
 - LHC combination: $BF(B_s \rightarrow \mu^+\mu^-) < 1.08 \times 10^{-8}$ at 95% CL
 - CDF: $4.6 \times 10^{-9} < BF(B_s \rightarrow \mu^+\mu^-) < 3.9 \times 10^{-8}$ at 90% CL
- $$BF(B_s \rightarrow \mu^+\mu^-) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$$
- LHC and CDF confidence intervals overlap.
 - More data needed to accurately determine $BF(B_s \rightarrow \mu^+\mu^-)$